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Cross-disciplinary design based on the digital factory as a boundary object

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Abstract

In the domain of developing production systems, the design of a good factory is typically distributed over many disciplines and organizations to cover all involved technologies and levels of detail (process, logistics, machinery etc.). Modelling and simulation used to support the design process within each of the disciplines typically represent different contexts and perspectives. To cross the discipline borders and share experiences, to encourage innovation and make holistic decisions, one challenge is to interrelate various digital models and to reach a mutual system understanding between stakeholders.

This paper presents a study based on principles from Social Science, Production Engineering, Computer Science and Information Design to address cross-disciplinary collaboration. Principles concerning visual communication and theories in regard to tangible boundary objects are used to clarify how to describe production system interdependencies in a digital factory context. Work in process of implementing a digital factory framework based on the principles is described, with a use case demonstrating the development of a digital factory for a new type of automotive vehicle.

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Keywords: Multi-disciplinary collaboration; digital factory; visualisation

1. Introduction

Demands on individualization, new technologies and sustainability have led to an increased demand on innovations concerning new materials, technologies and system solutions. These increased needs for innovation and global collaboration within industry rises the needs for coordinating various disciplines within an organization, sharing information, experiences and creating an understanding of the common system.

In the domain of developing production systems, the design of a good factory is typically distributed over many disciplines and organizations to cover all involved technologies and levels of detail (process, logistics, machinery etc.). Modelling and simulation of processes, layouts and workspaces is often used to support the design process within each of the disciplines, but these models typically represent different contexts and levels of detail and reside in different IT-systems using different formats and vocabulary. In order to cross discipline borders and get a systems understanding, one challenge is to interrelate various digital models and to reach a mutual understanding between stakeholders.

We as human beings have the ability to remember past worlds and imagine many possible future worlds. However, how we image the future depends on previous experience and pre-knowledge [1]. In addition, any one person cannot overview and manage all aspects of current, past and future worlds. For each task at hand, we select and describe the perspective that seems important, splitting the world up in portions. And thus we don´t have a unified view of everything, but a set of different perspectives and sometimes contradictory, mental models. So for a common systems perspective, these different perspectives and models need to be coordinated.
The aim of this paper is to problematize and elucidate some of the crucial aspects of using theories of boundary objects, together with modeling and visualization principles to manage and coordinate different perspectives [2]. The term boundary

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object refers to an object that serves as an interface or crossing point between different social worlds [3].

Our hypothesis is that we can use a digital factory as a common boundary object to support interdisciplinary communication and systems thinking when developing production systems.

The study is based on research in Production Engineering and Information Design, including principles and methods from Computer Science and Social Science for coordinating large volumes of information. Principles from Information Design with focus on visual communication [4,5,6,7] and theories in regard to boundary objects [2, 3] are used to clarify how to represent and communicate the interdependencies between different levels of a production system in a digital factory context. Worlds in this concept are to be understood as different practices, cultures or knowledge domains. Visualizations of future stages in factory planning can work as boundary objects between different stakeholders that have various pre-knowledge and experience.

Visualization for information and knowledge transfer has long been an integral part of simulation based analysis [8]. Still, there is a lack of interfaces that fully match the needs and exploit the potential of using visuals in industry. For example, though some vendors provide 3D visualizations of how products move through a factory, this is a quality that is seldom asked for by either production engineers or managers. A better way of visualizing bottle-necks, utilization of resources and buffers could help making decisions concerning re-planning or machine investments. Further, there is a growing need to visualize knowledge about the behaviour of the system. Typical examples are detection and monitoring of transient phenomenon in the flow, and forecasting of behaviour and performance based on data from multiple simulation results.

When designing a factory layout, a variety of aspects need to be taken into consideration such as ergonomics and safety, which means that an understanding of space is required. Layouts are ideally carefully represented in models which make the spatial relations such as distance, size and volume justice [9]. From design research (product design, build design and spatial design) there are contributions for identifying what is essential in design process´ considering communication within the design team and for communication with different stakeholders [10]. Based on this knowledge, work in progress of developing a digital factory framework, using the digital factory as a boundary object, is presented.

The framework comprises principles for designing the digital factory as well as methods for using it to support interdisciplinary communication and systems thinking.

The digital factory comprises several models with different purposes, perspectives and levels of detail of a production system. The domains of process planning and factory design within machining and assembly are covered. Interdependencies between, and challenges within, individual domains are captured by describing the design process and how key properties of alternative solutions are evaluated within each domain, as well as simulating how changes in the prerequisites would affect the whole system. The selection of a new automotive production system and detailing how this would be designed was done together with industrial experts to assure the industrial relevance.

2. Theoretical foundation

Visual communication, information design and boundary object theory have in common that they all address aspects of representing and interrelating various perspectives of a system. They address either human or computer aspects of how various perspectives can be communicated and interrelated to create a whole, or reversely, how a whole can be divided into separate perspectives to be manageable.

In computer science the focus is on modeling and communication of digitalized information, whereas visual communication is focused on the communication of information to and between humans.

2.1. Visual communication

Previous research that outlined theories regarding visualization and how human beings perceive visuals and the ability to use them is still fundamental for the discussion about digital factory. Graphic design research is mainly based on research in and theories that goes back to Gestalt theories such as Kurt Koffka, Principles of Gestalt Psychology [4] and scholars focusing on the relation between visual representations and mental images like Kosslyn *Image and the Brain* [11]. Gestalt theories also concern how humans think and understand in relation to visual images, as elaborated by Rudolf Arnheim in *Visual Thinking* [7]. Two important contributions taking an interdisciplinary approach are Eugene S. Fergusons *Engineering and the Mind´s Eye* [12], and Kathryn Henderson with *On Line on Paper, Visual Representations, Visual Culture, and Computer Graphics in Design Engineering* [13]. While Ferguson picks examples from history on how engineers have preferred the use of drawings for communication, Henderson has studied engineers in their practice. In the field of engineering design some studies have indicated how systematic use of visuals can support design thinking and facilitate the communication within the team [14]. However, there is a lack of more recent research based on visual theories related to engineering or manufacturing industry. In an information lifecycle, various kinds of visual representations are important for communication on different levels within an organization or between organizations. It influences individual thinking, communication in the design process and the decisions on different levels. When design processes, methods and tools change, the meaning and role of conventional representations of information may change, creating a need for new forms of representations [14]. New methods, procedures and computer tools require designers to represent design information differently and also to think about old problems in new ways.

2.2. Information architectures and management

The structuring and decomposition of complex information has long been an issue in computer science. The design principle ”Separation of concerns” SoC [15] was first presented in 1974 as a principle for separating a computer program into distinct sections, such that each section addresses a separate concern. This principle of modularity is the basis for the object oriented and service oriented architectures.

In general, a model is a description of something else, often simplified in some sense. The model has a purpose of answering questions concerning certain aspects (appearance, behavior, decomposition etc.) of the entity which is being modeled [16]. A model should preferably have a defined purpose, viewpoint (user perspective) and detailing level [17]. A digital model could be comprehensive, containing a lot of information out of which a selection could be made to answer questions from various perspectives. Alternatively, the model could be a combination of various distributed model perspectives, where each perspective makes its own simplifications. This reflects the issue of understanding how to combine many simplified part models into a whole. Since each part model makes its own simplifications, the combination of all part models may be inconsistent [18]. The concepts of 'views' and 'contexts' have been used frequently to define ways of abstracting away underlying data model complexities and provide a tailored way of accessing the data, e.g., to enable various perspectives of a common product. These contexts should be easily configurable to meet the specific user requirements. Database views are the initial approach, albeit limited to relational databases. These are stored queries, which e.g., can perform joining processes, apply aggregate functions and hide columns (SO/IEC 9075-1, 2011). The ISO 10303 (STEP) standard provides in part 41, Generic data models (ISO 10303-41, 2005), an application-context-schema, which allows specification of an application domain, product domain and lifecycle stage, to aid in the interpretation of the model. However, STEP does not provide mechanisms for defining the contexts from a semantic business point of view. As a way to combine generic information standards with contextual semantics Kjellberg [19] presented a machine tool model with several different views of a machine tool, for different purposes, represented using the STEP standard mapped to concept ontology.

Commercial PLM systems use contexts to specify the details of the product configuration, e.g., revision, state, variant, effectivity date. In [20], a viewpoint definition is introduced, with people, model, and tool levels, which are used to specify viewpoint contracts between different domains.

2.3. Boundary objects

Star and her college James R. Griesemer [3] shaped the frame for the theory that can be interpreted as follows; boundary objects are objects, or entities, which are both enough mouldable to be adopted for different needs and limitations of the parties that are employing them, but at the same time strong enough to maintain a common identity across sites. A boundary object is weakly structured in common use, and becomes a strongly structured object or entity in individual-site use [3]. Consequently, a boundary has its various meanings to people employing them from different profession-areas. Still the structure is common enough to make them detectable as means of translation. The value is that a boundary object can facilitate communication and mutual learning when people from different spheres or with different horizons of understanding are solving tasks [21].

Star suggested that boundary objects are simultaneously concrete and abstract, specific and general, conventionalized and customized, and suggested four types of objects: repository, ideal type, coincident boundaries and standardized forms. In our particular case, the visualizations and the instruction texts in development in the digital factory demonstrator, could be classified as entities containing both coincident boundaries and standardized forms. That means parts of the demonstrator could work as a platform for communication more or less ad hoc in a situation while others are more consistently used.

Boundary objects facilitate communication between different stakeholders. Communication is not static, it is dynamic and according to Merten [22] communication acts in three fundamental dimensions. First, *temporal* communication processes directly impact themselves. Secondly, *factual* communication processes require factual statements, but also require meta-statements to make communication understandable and targeted. Thirdly, *social* communication processes are orientated towards others. Here we consider culture as something that could be related to every group of stakeholders, in an organization involved in a co-creation activity. In this paper we focus on how the visualization in a digital factory works as a boundary object since visualization make ideas about the future tangible. Through the possibility to point at different parts, it is made sure that everyone understands what is in focus and can discuss the same thing. The digital factory aims to support the communication acts in the three dimensions: temporal, factual and social.

3. Demonstrator of digital factory

The demonstrator concerns developing and using a digital factory for model based development of a new factory for manufacturing a new type of vehicle called RCV (Fig. 1). The RCV is a light-weight design with a carbon fibre sandwich base plate, drive by wire technology and superior road holding qualities enabled by active electric individual steering, camber and traction/braking on each wheel.

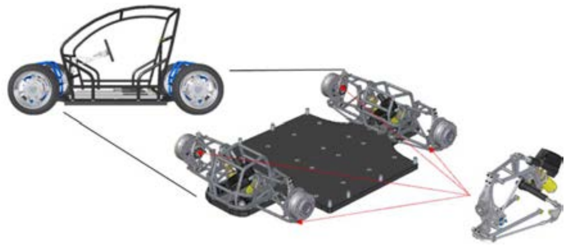

Fig. 1. The chosen product - RCV Vehicle with suspension and upright

Initially there is an existing prototype of the RCV and the task in the demonstrator is to industrialize this prototype, developing a complete new factory, a so called "Green field". The total planned capacity is 90.000 vehicles per year with a plan to extend the capacity to 150.000 but also to decrease it to 40.000/year if necessary. Two main models with different volumes are planned for: a two-seater and a four-seater with the main variation being the length of the base plate and the number of seats. In our case, we have divided the production into three factories: the manufacturing of the composite base plate; the machining of the wheel suspension upright - central to the road holding qualities - and the final assembly of the whole vehicle (Fig. 2). All other components and processes are out of scope and assumed to be purchased/sourced.

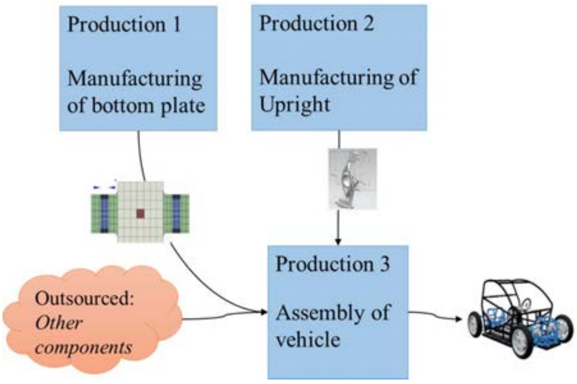

Fig. 2. Factories for RCV

The three main domains in focus are, simply described: 1) planning the processes which adds value to the product and are dependent on the product features and decomposition as in assembly cell design or machining process planning; 2) material flow design – planning the flow of material between the processes mainly based on varying product volumes and cycle times of the processes, and 3) factory layout design – designing the layout for efficient utilization of space, making sure that machines, equipment and products fit spatially according to regulations and the planned flow. To describe the system, a digital factory is developed, with models of the factory processes, equipment and layouts. In this digital factory, virtual manufacturing is performed in terms of 1) simulation of the machining processes for manufacturing the upright and 2) discrete event simulation for simulating the material flow in the assembly line.

The industrial context is realization of products with a high degree of added value, where demands on quality, productivity and lead time are high. Together with industrial partners actively working in this context, the following industrial challenges were selected:

1. Ability to adhere to ergonomics and safety regulations in layout design – for example making sure that there is enough space so the operators in the assembly shop do not step into the truck lane.
2. Ability to design for logistics in the final assembly shop – for example balancing the required space for internal buffers with the frequency of supplying material.
3. Ability to compare process planning concepts considering cost, quality and productivity, both from the internal machine processing perspective and in a wider factory scope.
4. Ability to adjust to fluctuations in the demand of volumes for different product variants in a factory – for example adapting to changed market demands concerning 2- seated versus 4-seated RCVs.

To illustrate the key aspects in each domain, alternative solutions are designed and analysed: for process planning of the upright; for layout of the machining factory; and for process planning and layout of the assembly factory.

To illustrate the effects of changes on the system as a whole, an unexpected change in demanded product volumes and variants is introduced. The material flow with the new volumes is simulated, leading to the insight that the new flow will not be feasible with existing processes. It is determined that a change is required to lower the cycle times which in turn will require redesign of, or different allocation of resources to, the assembly proesses. The new volumes also affect the manufacturing of the upright, with considerations concerning changing the process plans, number of machines (with consequences on the layout) or even redesigning the shape of the upright.

A third step of communicating the essence of each domain is through a simplified description of how an expert in the domain works. Experts know what functions and properties to focus on, what steps to take and what important constraints to consider. An example from conceptual factory design is starting by determining the types of and sequence of processes; then making a rough estimate of required resources and space for each process, always making sure to leave room for the required safety distances.

4. Applying the theories of visualization and boundary objects in the Digital factory use case

4.1. Visuals supporting factory planning

The core competence in factory planning is often more or less embedded and silent and related to the planner's knowledge domain praxis. In decision making situations where multidisciplinary teams need a mutual understanding and take decisions, it is important that the visuals in use have a design that supports understanding cross disciplines.

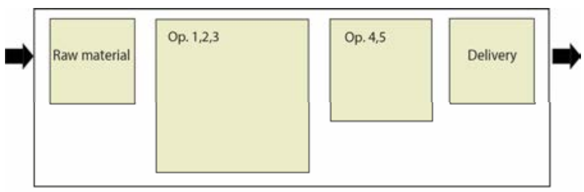

Fig.3. Shows estimated area for planned processes in a planned factory.

The visual representations in Fig. 3 and 4 are part of the demonstrator, showing two vital steps in the factory layout planning process. In general, they could be applicable to the layout of all of the production factories. The visuals are developed to be able to reflect the factory planners experience (knowledge) but are at the same time developed with regard to the interpretation potential when used in multidisciplinary teams. The visual in Fig. 3 roughly shows estimated areas for the planned processes, and the flow from raw material to delivery. In the next step (Fig. 4) the positions of the machinery are outlined. The machines are logically grouped in regard to safety and flow and the area that surrounds them includes space for the workers and maintenance personnel to move and work. The spaces are ergonomically reasonable for the planned processes. Furthermore, the process types are also separated and grouped. In this step of the planning it is possible to understand a bit more of what spaces are required for setting up the coming factory.

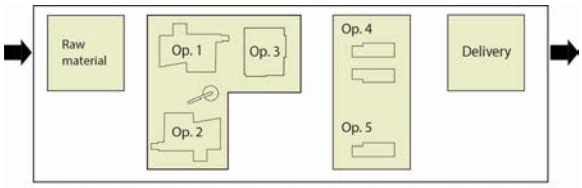

Fig.4. Shows estimated area for planned processes, positions and outline of the machinery.

4.2. The demonstrator as a boundary object

This use case is developed for the purpose of providing a general boundary object to support cross-functional collaboration. It is a demonstrator that is created with regards to the multimodal processes involved in interpretation and use of interactive interfaces and the design of all its parts and structures.

One assumption is that better decisions are made through an understanding of the system, the key qualities within each function/domain, and how choices made in one domain will affect others. A hypothesis is also that sharing key issues and solutions between domains cater for applying ideas from another area of expertise to one´s own context, thus supporting innovation. The demonstrator will allow the ability to visualize different stages from conceptual process planning to positioning of the machinery in a detailed factory layout. Visuals in every stage will work as a boundary object for the individuals that are involved, as exemplified in 4.1. Boundary objects are often weakly structured in common use [3]. Since the demonstrator aims to give an example of how a digital factory can work as a boundary object for different stakeholders, its design is simplified and focus on selected properties. Still the structure is general enough to make the different stages detectable as means for translation into the actual situation. That could be explained by the fact that visuals are at the same time concrete and abstract.

As in the example above, the block layout works as a boundary object for stakeholders in process planning and factory layout. It is abstract due to the lack of detail in both process sequence, appearance and interconnections of equipment (se Fig. 3). Still it is concrete enough to provide a good view of the grouping and proportions of processes on the factory floor. It is important to note that a selected visualization might also add constraints in a way that was not intended: since the processes are placed in a row they could easily be understood as if they have a fixed position.

Although the RCV is a real product, the manufacturing use case is fictitious. This has the advantage of providing a general case that is openly accessible and can be used by different companies. It also simplifies design of the models to focus on selected aspects while abstracting away others. Still, one challenge is to avoid making a toy, but to make the demonstrator and digital factory industrially valid, reflecting key industrial issues within each discipline/function/domain. We also assume that learning is improved when interesting and industrially valid challenges are in focus.

The method of the demonstrator is to: 1) Describe alternatives within each domain; 2) simulate cause-effect between domains; 3) describe the design process (Table 1).

Table 1 Three methods for describing the boundary object

Describe alternatives	**Simulate cause-effect**	**Describe design process**
Create and analyse alternative solutions in each domain; visualizing the key criteria, alternative solutions and how they fulfil the criteria.	What-if: make a change in preconditions and estimate, simulate and visualize the effects on the system and in the different domains.	Present expert knowledge of where to start, which the more important questions are to ask, and what steps to take.

The idea behind the layout design visuals are that: proportions and need of actual space can be discussed from quite simple outline sketches, without the use of 3D, in early phases of a planning process. 3D representations in this stage of a process could be both time consuming and therefore an expensive activity, but more important also misleading. The high iconicity of the 3D representations is often fooling the interpreter to think that all details are planned and solidly elaborated and thought through. Therefore, that type of representation is more useful in later phases of planning processes, and a higher level of abstraction is to prefer in early stages of factory layout planning. But since a high level of abstraction easily creates variations of understanding among stakeholders, a visual platform used as a boundary object can support a discussion that leads to a mutual understanding. Not forgetting that spoken or written language points out what to highlight from each perspective in all addressed visuals.

5. Conclusions

This paper presented work in progress, testing an idea to use a digital factory as a boundary object to coordinate multiple disciplines in factory design. The development of the digital factory framework is based on theories that go back to the 1970s in computer science and visual studies. The contribution was to combine these theories with ideas about boundary objects to better understand what is required from a demonstrator in order to work as a platform for communication and decision making.

The design and implementation of the demonstrator together with industry indicate that within each factory of the production there is an interest to compare alternatives from both a process and factory level perspective in order to make more holistic decisions when investing in new equipment. Visualizing possible factory layouts corresponding to a process planning concept provided an understanding of how different cycle times and choice of machines would affect the size of the factory. It indicated that seeing the layouts would provide an intuitive understanding of the possibilities and risks with each alternative, in addition to numerical KPIs given by calculations which are usually used for decisions concerning new investments.

We also wanted to test if it was possible to promote interdisciplinary communication through the digital factory and to promote applying ideas from one domain to another to support innovation. So far, this idea has not been possible to verify, but on the opposite, it seems that there is an initial lack of interest of engaging in the details of other disciplines.

The boundary object principle of balancing the concrete with the abstract is in our case exemplified by the block layout of a factory which is an abstract model that is understandable by both process planners and factory designers and can easily be related to more detailed models within each if these domains. It was fruitful to compare visual communication, information management and boundary object theory since they all address either human or computer aspects of how various perspectives can be communicated and interrelated to create a whole. The principle of boundary objects of combing the abstract with the concrete has a parallel in object oriented representations where interfaces between objects represent common concepts while objects internally have a deeper level of detail. Thus a boundary object represents an abstract interface which is designed to access more concrete internals, either the interface is represented as visuals interpreted by humans or interfaces interpreted by computer systems. We see this as a promising contribution towards a theory of information management which generalizes and combines methods from the domains of visualization and computer science to manage system complexity.

Although visuals are used a lot within various production system development applications, there is a lack of information presentation theory. Our approach is promising as starting point for such a theory of how to select and visualize information for the purpose of communication in production system development. Further studies which analyze and specify the exact information contents, and means of visualization, of each stage needs to be performed. These studies should cover to what extent the visuals for communication between disciplines are different from those used within each discipline, and if these visuals are boundary objects which reflect the important properties and information interfaces between domains rather than the details of the domain.

From the perspective of using existing ICT user interfaces as a basis for analysis, one problem has been the lack of user interfaces supporting collaborative conceptual design. On the other hand, such lack points to an important area of further research and development.

To conclude, we have experienced how the development of the digital factory demonstrator has served as a boundary object to coordinate our different perspectives from the social, production engineering and computer science research disciplines.

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